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Identifying groundwater compartmentalisation for hydraulic fracturing risk assessments

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Environmental significance statement

Hydraulic fracturing (fracking) is used to access unconventional petroleum resources. The rapid expansion of fracking, particularly in North America, has led to environmental concerns associated with the practice and ongoing research is addressing these issues. Groundwater contamination is a concern in England, where the Bowland Shale is about to be developed. Fracking fluid migration along high-permeability faults is a key concern, but recent research has shown the importance of low-permeability faults compartmentalising basins and affecting the long-term migration of fluids. This study proposes a method to identify compartmentalisation using the Bowland Basin as a case study. Results suggest that the adequate identification of compartmentalisation in shale basins may require dedicated groundwater sampling and the acquisition of new seismic reflection data.

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Abstract

An environmental concern with hydraulic fracturing (fracking) is that injected fluids or formation fluids could migrate upwards along high-permeability faults and contaminate shallow groundwater resources. However, numerical modelling has suggested that compartmentalisation by low-permeability faults may be a greater risk factor to shallow aquifers than high-permeability faults because lateral groundwater flow is reduced and upward flow through strata may be encouraged. Therefore, it is important that compartmentalisation can be adequately identified prior to fracking. As a case study we used historical groundwater quality data and two-dimensional seismic reflection data from the Bowland Basin, northwest England, to investigate if compartmentalisation could be adequately identified in a prospective shale basin. Five groundwater properties were spatially autocorrelated and interpolation suggests a regional trend from recent (<10,000 years old) meteoric groundwater in the upland Forest of Bowland to more brackish groundwater across the Fylde plain. Principal components analysis suggests two end-member brackish groundwater types. These end-members along with seismic interpretation suggest that a fault may structurally compartmentalise the northwest Bowland Basin. Furthermore, the Woodsfold fault structurally compartmentalises the southern Fylde and the Blackpool area provides evidence for stratigraphic compartmentalisation in

the Superficial Deposits. However, large areas of the Bowland Basin are not sampled and the influence of known faults on groundwater is therefore difficult to assess. Consequently, the adequate identification of compartmentalisation in prospective basins may require supplementing historic data with dedicated basin-wide groundwater monitoring programmes and the acquisition of new seismic reflection data in areas of poor coverage or quality.

View Article Online
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1. Introduction

The commercial extraction of oil and gas from low-permeability unconventional reservoirs, such as shale, can be achieved using hydraulic fracturing (fracking). Fracking involves the pressurised injection of fluid, usually water with chemical additives, to create hydraulic fractures which increase the reservoir permeability. The application of multi-stage fracking in horizontal boreholes to exploit shale reservoirs has led to various environmental concerns, for example induced seismicity, surface spills, and water contamination.[1-3] Observed subsurface groundwater contamination from fracking sites is rare and highly,[4-6] but groundwater contamination remains one of the greatest concerns of the public, governments, and regulatory bodies.[7]

Assessing the contamination risk of shallow groundwater resources at tens to hundreds of metres depth from the injection of fracking fluids at several kilometres depth requires the identification of pathways. Geological faults are generally considered the highest risk natural pathway between shale reservoirs and the shallow subsurface, as evidenced by numerous numerical models focussing on fluid injection into high-permeability fault structures.[8-13] However, more recent numerical modelling found that for fluid injection situated between faults (a more likely development scenario because operators aim to avoid fluid injection into faults), it was the scenarios with low-permeability faults that resulted in the highest risk to the shallow aquifer.[14] This was because the modelled low-permeability faults acted to structurally compartmentalise groundwater in the basin, discouraging lateral flow and encouraging upward flow through strata in the presence of a vertical hydraulic head gradient.[14]

View Article Online
DOI: 10.1039/C8EM00300A

Compartmentalisation can also be caused by stratigraphic changes, for example aquifers vertically separated by low-permeability formations or the lateral pinch-out of the aquifer bodies. Both structural and stratigraphic groundwater compartmentalisation are analogous to the compartmentalisation of petroleum reservoirs. In simple basins where stratigraphic units extend undisturbed for 100s to 1000s km and faulting is of minor importance for basin structure, compartmentalisation of petroleum resources and groundwater is unlikely to be an important effect. However, for basins where stratigraphic changes and faults are common, for example offshore and onshore basins of the UK, compartmentalisation is an important effect.[15-18]

Groundwater compartmentalisation can be identified from observations of hydraulic head, water table height and groundwater geochemistry, temperature and age,[17, 19] although very different hydrodynamic interpretations can be made from the same data.[20] Whereas the identification of compartmentalisation in petroleum reservoirs is normally driven by economic reasons,[15] the main driver for identifying groundwater compartmentalisation is the environmental protection of water resources.[17] Compartmentalisation can induce flow directions different to regional trends, create areas of no flow or reduced flow, and produce large variations in groundwater levels, temperatures and compositions.[21-23] All these effects have implications for groundwater abstractions, fluid injections, and the potential subsurface movement of contaminants. Consequently, there is a need to be able to adequately identify groundwater compartmentalisation for environmental risk assessments of fracking operations.

In this study we propose an approach for identifying groundwater compartmentalisation in prospective shale basins. Because high-permeability faults are currently considered higher risk basin features than compartmentalisation by low-permeability faults, compartmentalisation is not necessarily a focus in environmental risk assessments. We use historical data (groundwater quality data and seismic reflection surveys) from the Bowland Basin in northwest England, where the mid-Carboniferous Bowland Shale is hypothesised to be prospective for shale gas (Fig. 1),[24] to identify

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compartmentalisation and consider if current data enables adequate identification across the basin. We analyse groundwater quality data using spatial statistics, interpolation, standard groundwater plots, and principal components analysis. These results are then directly related to subsurface basin geology interpreted from seismic reflection data. To our knowledge this is the first study to integrate groundwater quality data with seismic reflection data to specifically identify groundwater compartmentalisation prior to widespread development of a shale basin.

2. Approach and Methodology

The approach taken was to integrate environmental groundwater quality data with subsurface geology, interpreted using two-dimensional (2D) seismic reflection data, from a prospective shale basin undergoing initial development; the Bowland Basin, northwest England. The data were collected prior to widespread shale exploitation (only one borehole targeting shale has been fracked in the Bowland Shale) and were unrelated to shale exploration. They are therefore opportunistic in terms of environmental risk assessment needs. The approach of combining groundwater and seismic reflection data could be used in other prospective basins globally to identify groundwater compartmentalisation as part of the exploration stage prior to fracking. By adequately identifying groundwater compartmentalisation, operators and regulatory bodies may be better able to assess areas where shallow groundwater resources are more, or less, vulnerable to contamination from the potential upward migration of fracking or formation fluids. This could lead to improved vulnerability maps and consequently help guide the drilling locations of boreholes.

2.1. Groundwater quality data

Water quality data for Lancashire and Cumbria, northwest England, were downloaded from the English Environment Agency's (EA) Water Quality Archive[25] for the years 2000-2016, inclusive. Groundwater samples within a rectangular area of interest were extracted (Fig. 1). This area of interest covers the Fylde (the low lying coastal plain) where the Bowland Shale is prospective and fracking operations are focussed, for example the Preston New Road and Rose Acre Wood sites

DOI: 10.1039/C8EM00300A

(Fig. 1). Only those groundwater samples collected as part of routine monitoring were considered and no samples noted as coming from pollution incidents or collected as part of specific investigations were included so as not to bias the dataset in favour of specific sites or specific groundwater properties. Entries located offshore or with miscellaneous names and arbitrary grid references were also removed. Fourteen common groundwater properties were extracted; alkalinity to pH 4.5 as $CaCO_3$, barium, calcium, chloride, conductivity at 20 and 25°C, iron, magnesium, manganese, pH, potassium, sodium, strontium, and sulfate as SO_4. These groundwater properties were sampled across 96 unique locations. To average out irregular timings between groundwater samples and seasonal variations in groundwater chemistry, groundwater properties at each unique location were mean-averaged for the time period 2000-2016. This approach was considered appropriate because the size and distribution (both spatially and temporally) of the dataset means that the variability or effect of individual measurements is limited. Measurement errors are not included the EA Water Quality Archive. Therefore, within this study and unless otherwise stated, measurement error was assumed to be ± half the smallest division stated in the archive.

The Global Moran's I test in ArcMap 10.3 (see Supplementary Material) was used to investigate if any groundwater properties were significantly spatially autocorrelated. The influence of data at a sample location was assumed to be inversely related to distance from the location. Distances between sample locations were calculated using the Euclidean distance, with the threshold distance set so that every sample location had at least one neighbouring sample location. Statistical significance was judged at the 95% probability (p-values $\leq$0.05) of the spatial distribution not being the result of random chance. This approach further mitigates against temporal variations in the groundwater samples because if differences in sampling date were causing a comparatively high degree of variability between locations then the data would fail the Global Moran's I test at the defined probability. Groundwater properties showing statistically significant spatial autocorrelation were interpolated using kriging. Prior to kriging the numerical distributions of the groundwater properties were qualitatively assessed using histograms and normal quantile-quantile (Q-Q) plots.

View Article Online
DOI: 10.1039/C8EM00300A

Groundwater properties that were not normally distributed were log transformed prior to interpolation and re-examined to test for normality – no further transformations were found necessary. The automated iterative cross validation technique in ArcMap 10.3 was used to maximise the model fits of the semivariograms for each statistically significant groundwater property. Interpolation without predefined barrier features was chosen to prevent biasing the results by pre-defining compartmentalisation.

A Global Moran's I test was run under the same parameters as above to investigate if groundwater total dissolved solids (TDS) were spatially autocorrelated across the Bowland Basin. TDS values were estimated by summing the concentration of the major cations (Na^+, K^+, Ca^{2+}, Mg^{2+}) and anions (Cl^-, SO_4^{2-}, HCO_3^-) at each location. Because the EA data contained only two HCO_3^- measurements across the study area and timespan, HCO_3^- concentrations were approximated using the atomic mass ratio (0.61) of HCO_3 to $CaCO_3$ and the alkalinity to pH 4.5 as $CaCO_3$ measurements. Where one or more cation or anion measurement was missing at a location, the location was ignored for TDS estimation; only 90 of the 96 unique locations had the complete suite of major cation and anion data for TDS estimation. Error in TDS was calculated from the square root of the summed squares of the major cation and anion measurement errors. The cation and anion data were also plotted on Piper and Gibbs plots[26, 27] and used to calculate sodium to chloride ratios (Na:Cl) to further analyse groundwater chemistry. The Piper plot was created using GW_Chart (v.1.29.0.0).[28]

Principal components analysis (PCA) was performed on 56 unique sample locations where all spatially autocorrelated groundwater properties were present and TDS could also be estimated. PCA was chosen because it is a multivariate statistical technique which can be used to reduce large numbers of observations while still maintaining the majority of information. Prior to the PCA, the groundwater properties were z-transformed to normalise each property. This transformation allowed the comparison of properties with different units, for example conductivity was measured in μS/cm.

View Article Online
DOI: 10.1039/C8EM00300A

Principal components (PCs) in the analysis were chosen based on selecting all PCs with an eigenvalue >1 and the first PC with an eigenvalue <1.[29] Principal components with an eigenvalue >1 represent components that explain more of the underlying variation than any of the original variables. The PCA was performed in Minitab (v18). Interpretation of groundwater end-members, trends and outliers in the PCA results was undertaken using scatter plots of PC values. No end-members, trends or outliers were known or assumed prior to this interpretation.

A limiting factor of the EA Water Quality Archive is that it does not contain the depths or geological formations groundwater samples were taken from. To provide some depth constraint on the groundwater samples, groundwater boreholes from the BGS Onshore GeoIndex[30] were extracted across the area of interest. Sample locations from the EA Water Quality Archive were manually matched with groundwater borehole locations from the BGS Onshore GeoIndex using geographic coordinates and location names. BGS borehole depth and aquifer designation were taken as proxies for which geological formation EA samples were taken from.

2.2. Geological and geophysical data

Geological and geophysical data for the Bowland Basin were collated from the UK Onshore Geophysical Library[31] to interpret and discuss the groundwater analysis results in terms of subsurface geology. These data included formation top data from petroleum boreholes and 2D seismic reflection data. Interpretation of the seismic reflection data was guided by the formation top data, published interpretations across the area, and British Geological Survey (BGS) maps.[32-35] Previously interpreted seismic lines available in the literature included GC83-352,[36, 37] GC87-372 ,[38] GCE-86-DV37,[39] and composite regional sections.[24, 40]

2.3. Interpreting compartmentalisation

The interpretation of compartmentalisation draws from both the seismic reflection and groundwater quality data. In the seismic reflection data faults may be observable and the interpretation of horizons across the Bowland Basin will indicate any juxtaposition of geological formations across the faults. Where low-permeability formations lie juxtaposed against high-permeability formations, a barrier (no flow) or baffle (reduced flow) to groundwater flow may be formed. Even when low-permeability formations are not juxtaposed the fault core may act as a barrier or baffle due to clay smearing, cataclasis, compaction, and cementation .[19] Large contrasts in groundwater quality either side of the fault may then support the barrier or baffle hypothesis. Conversely, exceptions to any regional trends in groundwater quality data or the presence of different groundwater types may indicate the presence of compartmentalisation. Seismic reflection data can then be used to see if there are any geological structures or stratigraphic features that may account for the difference in groundwater.

3. Geological history of the Bowland Basin

This study uses the Bowland Basin as a case study for identifying compartmentalisation. Because the extent and formation of the Bowland Basin has been described and modified by various authors in the literature,[24, 41, 42] it is necessary to define what is considered the Bowland Basin in this study; the area bounded to the northeast by the Craven Fault System, to the southeast by the Pendle Fault System, and to the west by the East Irish Sea Basin.[24] Much of the Bowland Basin covers the Fylde coastal plain of Lancashire, which is where the Bowland Shale is prospective and fracking operations are currently focussed (Fig. 1).

The Bowland Basin initiated in the Early Carboniferous as a result of extensional rift faulting, leading to the deposition of basin-wide organic rich shales (Bowland Shale and Hodder Mudstone) and carbonates (Fig. 2).[42] A minor period of inversion may then have occurred, based on reverse faults in the Bowland Shale terminating at the base of the overlying Millstone Grit Group.[37] The overlying Millstone Grit Group and Lower Coal Measures are hypothesised to have formed during a thermal sag phase following the main rifting event and possible minor inversion.[42] The Late Carboniferous was marked by the Variscan Orogeny, which led to inversion of the Bowland Basin

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and substantial erosion of the Millstone Grit Group and Lower Coal Measures. The Variscan Unconformity can be observed on seismic reflection data from the Bowland Basin where dipping Carboniferous sediments are truncated by sub-horizontal Permo-Triassic sediments.[40]

Permian sediments in the Bowland Basin comprise of the Collyhurst Sandstone and the Manchester Marl. The deposition of the Collyhurst Sandstone appears to have been controlled by a second phase of extensional faulting.[42-44] The Collyhurst Sandstone is present in the Elswick Graben (bounded to the east by the Woodsfold Fault and to the west by the Larbeck and Thistleton Faults), but is absent on the structural high west of the Thistleton and Larbreck Faults (Fig. 2).[42] However, the Collyhurst Sandstone was observed in the Preese Hall 1 borehole further west of the structural high, supporting the hypothesis that it exists as a pinchout edge.[45] The Manchester Marl is considered to exist across the Bowland Basin (Fig. 2) and form a regional seal unit to the underlying strata.[46, 47]

Episodes of crustal extension continued during the Triassic, resulting in the deposition of the fluvial dominated Sherwood Sandstone Group and the overlying Mercia Mudstone Group. The Sherwood Sandstone Group in the Bowland Basin comprises of the stratigraphically lower and less-permeable St Bees Sandstone and the stratigraphically higher and more-permeable Sherwood Sandstone.[48] Jurassic and Cretaceous sediments are mostly absent from the Bowland Basin, most likely due to uplift and subsequent erosion in the Palaeogene followed by Alpine Orogeny-related inversion in the Neogene.[42, 49] The uplift also eroded the Mercia Mudstone Group in the eastern Fylde. Consequently, the Sherwood Sandstone directly underlies the Superficial Deposits in the eastern Fylde but is confined by the Mercia Mudstone Group in the western Fylde.

Regional uplift continued into the Quaternary along with eastward titling of the Bowland Basin.[42] Quaternary glaciation led to the widespread deposition of superficial glacial tills and sands across the basin. The glacial deposits have been further added to by blown sands and tidal alluvium.[32-35]

4. Hydrology and Hydrogeology of the Bowland Basin

View Article Online
DOI: 10.1039/C8EM00300A

Rainfall over the Bowland Basin can be split into two areas based on elevation. Over the low-lying Fylde Plain, which is predominantly arable land, average rainfall is <1,000 mm/year. Further east at the higher elevations of the Forest of Bowland, where land is moorland or rough pastures, average rainfall is greater at ~1800 mm/year.[50] Similarly, the river catchments of the Bowland Basin can be split into two areas. In the north of the basin the River Wyre originates in the Forest of Bowland before running onto the Fylde Plain, through Garstang, and eventually ending in the south of Morecambe Bay. The River Ribble is located in the south of the Bowland Basin and originates further inland than the River Wyre; starting in the Yorkshire Dales. From the Yorkshire Dales the River Ribble runs south then south-westwards, skirting the southern edge of the Forest of Bowland before running through Preston and into the Irish Sea.

The Sherwood Sandstone forms the principal aquifer in the eastern Fylde and the Millstone Grit forms the aquifer unit across the Forest of Bowland. The contact between these two formations is at the eastern edge of the Fylde and is marked by unconformable or faulted.[50] Initial groundwater models of the Fylde considered recharge of the Sherwood Sandstone from good hydraulic continuity between the Sherwood Sandstone and the adjacent Millstone Grit.[51] However, abstraction data indicates that recharge from the Millstone Grit is relatively minor in the northern Fylde and absent in the central Fylde. It is alternatively suggested that the majority of recharge occurs as vertical leakage through the overlying Superficial Deposits where low-permeability boulder clay is absent.[50, 52] In the southern Fylde near the River Ribble, inflow from the Carboniferous strata is considered more significant, although north-south trending horst and graben faults reduce horizontal flow.[53] Groundwater flows across the Fylde are towards Morecambe Bay in the north and the Ribble Estuary in the south.

Public and private groundwater abstractions in the Bowland Basin are focussed on the Sherwood Sandstone in the eastern Fylde, with few boreholes penetrating the Sherwood Sandstone

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DOI: 10.1039/C8EM00300A

in the western Fylde and no current abstractions.[50, 54] Consequently, little is known about groundwater in the Sherwood Sandstone across the western Fylde where fracking operations are currently focussed. However, one recent borehole at Rose Acre Wood has confirmed brine at depths of 360-500 m in the Sherwood Sandstone[55] and groundwater quality across the remainder of the western Fylde is hypothesised to be of poorer quality than in the east because the Sherwood Sandstone lies at greater depths (due to its westerly dip) and is confined by the overlying Mercia Mudstone Group.[56]

5. Results

5.1. Depth control on sample locations

Of the 96 unique locations we were able to match the coordinates and names of 71 boreholes in the EA Water Quality Archive with the BGS Onshore GeoIndex (Table S1); 50 with exact coordinates and names, and 21 with similar coordinates and names. We were unable to match 25 locations with boreholes in the BGS Onshore Index. The sampling frequency for different geological formations is given in Table 1 and the spatial distribution of sampled geological formations can be seen in Figure 1. Two of the 71 matched sample locations had the aquifer classification "No Aquifer". One of these locations is the Kirkham Borehole SD43/20 in which groundwater in the Mercia Mudstone Group has been sampled[57] (Fig. 1) and the other sample was taken at a depth of 23.6 m, suggesting it is located in the Superficial Deposits. These two samples were re-classified based on this information. The Kirkham Borehole SD43/20 is the deepest borehole in the dataset (depth of 445 m) and therefore all boreholes sample the shallow groundwater system.

Geological formation	Number of boreholes
Superficial Deposits	23
Mercia Mudstone Group	4
Sherwood Sandstone Group	10
New Red Sandstone Supergroup	1
Carboniferous (Limestones, Shales, Coal Measures, Gritstone, Undifferentiated)	17
Unknown	41

Table 1: Groundwater borehole frequency of different geological formations in the Bowland Basin.

5.2. *Spatial autocorrelation and interpolation*

View Article Online
DOI: 10.1039/C8EM00300A

The EA data used consists of 4865 samples across 96 unique locations (Table S2). Mean-averaged values of the 14 groundwater properties at each location are presented in Table S1. Of the 14 groundwater properties tested for spatial autocorrelation using the Global Moran's I test, alkalinity to pH 4.5 as $CaCO_3$, calcium, conductivity at 25°C, magnesium, and potassium showed statistically significant spatial autocorrelation (Table 2). For the remaining nine variables it could not be statistically ruled out that their spatial distribution was due to random chance. The five groundwater properties showing statistically significant spatial autocorrelation were log transformed prior to interpolation because they were not normally distributed. All five groundwater properties generally showed increases from northeast to southwest across the study area and the concentrations of calcium, magnesium, and potassium increased by factors of 10-1000 towards the Fylde coastline (Fig. 3). An obvious exception to this trend is the Kirkham Borehole SD43/20, which shows reduced alkalinity at pH 4.5 as $CaCO_3$ (Fig. 3a). A comparison of Table 2 with Table S1 confirms the unusual nature of groundwater in the Kirkham Borehole SD43/20; the borehole has the highest values in our dataset for calcium, chloride, conductivity at 20°C, magnesium, sodium, strontium, and sulfate as SO_4. Specific conductance was not measured in the Kirkham Borehole SD43/20 but would be expected to be elevated because of the elevated ion concentrations.

Groundwater property	Number of locations	Units	Assumed measurement error	Minimum value	Maximum value	Mean value	Standard deviation (±1σ)	p-value
Alkalinity to pH 4.5 as $CaCO_3$	96	mg/l	0.5	5.0	1263.1	346.6	237.3	0.000
Barium	46	µg/l	0.5	10.0	2830.0	196.3	415.3	0.195
Calcium	92	mg/l	0.5	1.2	1285.0	176.9	204.9	0.001
Chloride	95	mg/l	0.5	8.4	77000.0	1282.0	7969.7	0.485
Conductivity at 20°C	65	µS/cm	0.5	85.6	251500.0	5379.4	31095.4	0.749
Conductivity at 25°C (Specific conductance)	62	µS/cm	0.5	107.0	22300.0	2331.5	3565.1	0.002
Iron	91	µg/l	0.5	30.0	329871.4	22942.7	49983.0	0.071
Magnesium	92	mg/l	0.5	0.3	502.5	54.5	74.3	0.000
Manganese	91	µg/l	0.5	10.0	12943.3	1242.8	2373.6	0.275
pH	95	pH units	0.5	6.0	9.1	7.3	0.5	0.087
Potassium	91	mg/l	0.5	0.6	104.7	17.5	23.3	0.000
Sodium	91	mg/l	0.5	5.8	51550.0	819.8	5403.0	0.540
Strontium	71	µg/l	0.5	15.6	19050.0	1081.8	2347.8	0.513
Sulfate as SO_4	94	mg/l	0.5	1.0	6085.0	202.3	648.2	0.545
TDS*	90	mg/l	1	47	136487	2823	14406	0.477

Table 2: Descriptive statistics of groundwater properties extracted from the EA Water Quality Archive for the area of interest, along with p-value results from the Global Moran's I test. *Calculated (see Section 2.1).

5.3. *Total dissolved solids*

View Article Online
DOI: 10.1039/C8EM00300A

Estimated TDS concentrations for the 90 locations ranged over four orders of magnitude; from 47 ±1 mg/l to 136,487 ±1 mg/l. A Global Moran's I test on the TDS data could not rule out that the spatial distribution was the result of random chance (Table 2). The TDS data were therefore not interpolated. However, the TDS data were discretely mapped using a standard TDS classification[58] and a drinking water classification of TDS ≤250 mg/l (Table 3). The categorisation indicates that drinking type groundwater is related to higher topography (Fig. 4). The low lying Fylde has both fresh and brackish groundwater present (Fig. 4), although one location was classified as saline groundwater (G&G 92 at Clifton Marsh Landfill near the River Ribble mouth) and one location was classified as brine (Kirkham Borehole SD43/20) (Table S1).

Groundwater type	**TDS (mg/l)**	**Number of locations**	**Mean TDS (mg/l)**	**Standard deviation in TDS (±1σ) (mg/l)**
Drinking	≤250	10	116	74
Fresh	≤1,000	55	410	212
Brackish	1,000<TDS≤10,000	33	2,418	1,943
Saline	10,000<TDS≤100,000	1	15,273	-
Brine	100,000<TDS	1	136,487	-

Table 3: Groundwater type classification of samples based on total dissolved solids (TDS). Note that drinking type groundwater is also taken into account as part of fresh groundwater.

5.4. *Piper and Gibbs plots*

Figure 5a shows a Piper plot for the 90 locations where all major cations and anions were sampled. Groundwater samples from the Sherwood Sandstone Group and Carboniferous are predominantly Ca-HCO_3 type and categorise as drinking or fresh groundwater. Groundwater samples from the Mercia Mudstone Group classify as mixed-SO_4 type or Na-Cl type. These samples are either brackish groundwater or brine, respectively. Groundwater samples from the Superficial Deposits are generally mixed or Na-Cl type, and include both fresh and brackish groundwater types. However, the Na-Cl type groundwater samples are predominantly brackish groundwater samples.

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A Gibbs plot of the same 90 locations suggests that groundwater quality across the Bowland Basin is influenced by the three major processes (Fig. 5b); atmospheric precipitation, water-rock interactions, and evaporation-crystallisation. Drinking groundwater samples from the Carboniferous plot towards the precipitation trend because meteoric water has had limited time to chemically interact with rocks. The remaining Carboniferous samples and the Sherwood Sandstone Group samples are rock dominated, showing increased TDS because of increased chemical interaction time with rocks in the Bowland Basin. Superficial Deposit samples also plot in the area of rock dominance but also extend out towards sea water dominance, as do samples from the Mercia Mudstone Group.

5.5. Sodium and chloride data

Sodium and chloride concentrations and their ratios from the 90 locations with measurements are compared to a modern day sea water composition in Figures 5c and 5d. The brine sample from the Kirkham Borehole SD43/20 in the Mercia Mudstone Group is the only sample in the dataset more concentrated than sea water. This sample lies along the sea water trend, as do the majority of other samples. A separate trend consisting of Carboniferous and Unknown samples are enriched in sodium with respect to chloride. These samples generally have chloride concentrations from 10-100 mg/l, TDS from 250-1,000 mg/l (fresh groundwater), and Na:Cl ratios up to ~12 times that of sea water.

5.6. Principal component analysis

The PCA reduced the five spatially autocorrelated groundwater properties to three principal components based on their eigenvalues. These three principal components explained 93.1% of the variance in the data (Table 4). The first two principal components (PC1 and PC2) accounted for 79.0% of the variance (Table 4), but it was considered appropriate to include PC3 because the eigenvalue of PC2 was approximately one. All variables had positive loadings in PC1 (Table 4), indicating PC1 is a general concentration component and facilitates normalisation of the data for concentration variations. Potassium and magnesium had the highest loadings on PC1 and calcium had the lowest loading. Loading on PC2 was dominated by calcium (Table 4). Alkalinity to pH 4.5 as $CaCO_3$ was strongly negatively loaded in PC2 whereas potassium showed a much weaker negative loading. In PC3, alkalinity to pH 4.5 as $CaCO_3$ and calcium had strong negative loadings whereas specific conductance had a strong positive loading (Table 4).

View Article Online
DOI: 10.1039/C8EM00300A

	Principal Components				
Groundwater property	**PC1**	**PC2**	**PC3**	**PC4**	**PC5**
Alkalinity to pH 4.5 as $CaCO_3$	0.362	-0.506	-0.686	0.269	-0.263
Calcium	0.209	0.842	-0.479	0.126	0.047
Conductivity at 25°C (Specific conductance)	0.482	0.069	0.509	0.706	-0.073
Magnesium	0.535	0.100	0.201	-0.579	-0.572
Potassium	0.553	-0.144	-0.007	-0.279	0.772
Eigenvalue	2.9542	0.9940	0.7070	0.2509	0.0939
Proportion (%)	59.1	19.9	14.1	5.0	1.9
Cumulative (%)	59.1	79.0	93.1	98.1	100.0

Table 4: Results of principal components analysis for the groundwater properties which showed statistically significant spatial autocorrelation.

Further interpretation of the PCA results can be achieved through TDS coloured plots of PC2 versus PC1, PC3 versus PC2, and PC3 versus PC1 (Fig. 6). For PC2 versus PC1 three end-members (EMs), two trends, and a possible outlier group of samples can be identified (Fig. 6a). EM-A is groundwater with low TDS (i.e. drinking type groundwater) and forms the consistent EM for trends to EM-B and EM-C. The trends to EM-B and EM-C show increasing PC1, signifying increasing elemental concentrations, alkalinity to pH 4.5 as $CaCO_3$ and specific conductivity. This increase is also evident from the TDS colour coding, with a progression from drinking, to fresh, to brackish groundwater along the trends to EM-B and EM-C from EM-A. The trend to EM-B shows increasing PC2 with increasing PC1. Increasing PC2 is correlated with increasing calcium and decreasing alkalinity to pH 4.5 as $CaCO_3$. The trend to EM-C has decreasing PC2 with increasing PC1. The samples between the trends to EM-B and EM-C may represent mixing between the two trends plus outliers.

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The interpretation of PC2 versus PC1 is supported and furthered by plots of PC3 versus PC2 and PC3 versus PC1. These plots also show the trends to EM-B and EM-C and more clearly distinguish outliers (Figs. 6b and c). Trends to EM-B and EM-C show decreasing PC3 with increasing or decreasing PC2, respectively. Decreasing PC3 is correlated with increasing calcium and alkalinity to pH 4.5 as $CaCO_3$, but decreasing specific conductivity. However, the decreasing specific conductivity is not a real effect and is probably the result of skewing by some of the outliers, which have high TDS and specific conductivity. The proportions of EM-A, EM-B and EM-C in the 43 sample locations in the mixed zone between the EMs defined in Figure 6b can be calculated using line equations and Pythagoras. Sample locations in the east of the study area are generally at higher elevations and are dominated by EM-A (Fig. 7); of the 15 sample locations >100 m elevation above sea level, all but one have ≥64% EM-A. EM-A (i.e. 100% EM-A, 0% EM-B and EM-C) is located at the New Drop Inn Borehole. EM-A also dominates 21 of the 28 locations at elevations <100 m. Two locations, both located in Blackpool, are dominated by EM-B (Fig. 7). EM-B is located at the Blackpool Promenade No.9 Borehole. EM-C is located at the Jameson Road Landfill Site in the northwest of the Fylde. Three other samples in the study area are also dominated by EM-C (Fig. 7).

A comparison of the relative chemical compositions of EM-A, EM-B and EM-C shows that they differ (Table 5). EM-A has relatively similar proportions of major cations and anions whereas EM-B is dominated by calcium (57% compared to 13% in EM-A and 3% in EM-C) and EM-C is dominated by chloride (39%) and sodium (29%).

Groundwater property	**EM-A (%)**	**EM-B (%)**	**EM-C (%)**
HCO_3*	18	8	16
Calcium	13	57	3
Chloride	27	16	39
Iron	0	0	1
Magnesium	3	2	5
Manganese	0	0	0
Potassium	2	1	2
Sodium	17	11	29

Sulfate as SO_4	20	5	5

Table 5: Relative concentration proportions (to nearest whole number) of groundwater constituents for EM-A, EM-B, and EM-C. *Calculated (see Section 2.1).

The outlier sample locations identified in figure 6 can be sorted into two groups (Fig. 6b). The first group (6 sample locations) have high TDS (≥4288 ±1 mg/l compared to the next highest sample location in the PCA of 2460 ±1 mg/l) and their composition most closely resembles EM-C, i.e. enriched in chloride (49-73%) and sodium (18-29%). Five samples are located in the Superficial Deposits in Blackpool and one of unknown geological formation at Clifton Marsh Landfill. The second group of outliers can be distinguished from the first group by their high sulfate composition; 47-53% compared to 4-8%. All three outliers in the second group occur in the Mercia Mudstone Group in an area south of the River Ribble (Fig. 1).

6. Discussion

6.1. Evidence for groundwater compartmentalisation

6.1.1. Structural compartmentalisation

Regular groundwater monitoring in the Bowland Basin is focussed in the eastern Fylde on the principal aquifer for the region; the Sherwood Sandstone.[50, 54] Abstractions from the Sherwood Sandstone are located where it directly underlies the Superficial Deposits. In the southern Fylde this is to the east of the Woodsfold fault, where groundwater is fresh or marginally brackish. To the west of the Woodsfold fault the Sherwood Sandstone is confined by the overlying Mercia Mudstone Group. The Kirkham Borehole SD43/20 is the only borehole in our dataset that is known to monitor groundwater deeper than the Superficial Deposits west of the Woodsfold fault in the southern Fylde (Fig. 1); the borehole is 445 m deep and penetrates the Sherwood Sandstone at a depth of 367 m.[59] Groundwater samples from the Kirkham Borehole SD43/20 were taken in the Mercia Mudstone Group 240-260 m below the surface[57] and indicate Na-Cl type brine (Table S1). Na-Cl type brine has also been recently been sampled in the Sherwood Sandstone at the Rose Acre Wood site ~4.1 km to the north.[55] These brines contrast with the fresh and brackish groundwater east of the

Woodsfold fault, providing strong evidence that the Woodsfold fault compartmentalises groundwater in this area of the Bowland Basin (Figs. 8a and 9). Further support for this hypothesis comes from groundwater level data either side of the fault, which decreases from 5-10 m above Ordnance Datum (OD) east of the fault to 16.8 m below OD west of the fault.[56, 57] The compartmentalisation of the Sherwood Sandstone by the Woodsfold fault in this area of the basin may be the result of the large vertical offset across the fault, which is observable on seismic reflection data (Fig. 8a). The vertical displacement juxtaposes the Sherwood Sandstone against the lower-permeability St Bees Sandstone (Fig. 8a). The movement associated with this displacement may also have formed low-permeability granulation seams, crush textures and fault smears.[19] Further north where aquifer abstractions take place, the Woodsfold fault passes through the Sherwood Sandstone with less vertical displacement, meaning the Sherwood Sandstone is probably in greater continuity across the fault and groundwater is not compartmentalised (Fig. 9).

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Another possible example of structural compartmentalisation comes from the PCA. Graphical interpretation of the PCA results suggested two groundwater trends linked by common EM-A (Fig. 6b). EM-B and EM-C are both located on the Fylde coastline, but are ~13.6 km apart and show distinct chemical compositions. EM-B is calcium dominated whereas EM-C is sodium and chloride dominated. The distinct compositions suggest limited groundwater mixing between the two areas, implying a baffle or barrier may be present. Interpretation of the north-south trending seismic line GC-87-382_OM, which runs approximately from EM-C to EM-B, indicates the Preesall fault offsets the Sherwood Sandstone (Fig. 8b). We hypothesise that this fault may be acting as a baffle or barrier between the River Wyre and Blackpool areas, thereby compartmentalising the northwest area of the Bowland Basin (Fig. 9). However, it cannot be ruled out that the groundwater composition difference may result from stratigraphic compartmentalisation; EM-B is located in the Superficial Deposits and EM-C is of unknown depth (Fig. 1).

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In previous studies in northwest England structural compartmentalisation has been identified in the Carboniferous Millstone Grit[60] and the contact with the Sherwood Sandstone in the northern and central Fylde is considered a baffle.[50] Furthermore, the influence of faults on groundwater flow in the Sherwood Sandstone has been identified to the east of Preston, where north-south trending horst and graben fault structures are hypothesised as the reason for discrepancies between the original Fylde aquifer model simulations and observed groundwater levels.[53] Inclusion of the faults as baffles by a reduction in the east-west horizontal conductivity led to improvements in matches between model simulations and groundwater observations.[53] We also note that the most recent Fylde aquifer model contains faults in the Sherwood Sandstone in the central and northern Fylde, and that fault conductance varies by six orders of magnitude.[54] The conductance range implies that faults are considered to have varying influence on groundwater flow in the principal aquifer for the Bowland Basin.

6.1.2. Stratigraphic compartmentalisation

Stratigraphic compartmentalisation by low-permeability horizons has been identified in the Carboniferous Millstone Grit in northwest England.[60] However, evidence from this study for stratigraphic compartmentalisation in the Bowland Basin comes solely from the groundwater quality data of the Superficial Deposits. Eighteen sample locations within several hundreds of metres of each other in Blackpool show a mix of fresh and brackish groundwater with various relative ion concentrations and proportions of EM groundwater types. All 18 locations sample groundwater in the Superficial Deposits (Fig. 1) at approximately the same depth (9.3-17.3 m) (Table S1) and therefore the differences are unlikely to be due to groundwater salinity increasing with sampling depth. We instead hypothesise that the different groundwater types occur from compartmentalisation of the Superficial Deposits by the variety of deposit types (tidal flats, blown sand, peat, till, alluvium and glaciofluvial deposits) which can be found across the near-surface of the Fylde near Blackpool.[32, 35]

6.2. *Conceptual hydrogeological model for the Bowland Basin*

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In this section a conceptual model for groundwater flow in the Bowland Basin is proposed, focussing on the Sherwood Sandstone (Fig. 9). This model includes the western Fylde and thus expands on the Fylde aquifer model in the eastern Fylde.

The Sherwood Sandstone aquifer is recharged from precipitation by two mechanisms. In the southern Fylde near Preston groundwater in the Sherwood Sandstone is considered to recharged by precipitation on the high elevation (>100 m) Carboniferous formations in the Forest of Bowland and from vertical leakage through the Superficial Deposits. The groundwater flow from the Forest of Bowland to the Fylde is topographically driven by the ~500 m difference in elevation. In the northern and central Fylde, groundwater flow between the Carboniferous and Sherwood Sandstone is thought to be minor or absent. Instead the major recharge is considered to be vertical leakage through the overlying Superficial Deposits where boulder clay is absent.[50] This mechanism also probably accounts for the freshwater recharge of the Superficial Deposits across the western Fylde. Low TDS values (≤250 mg/l) across the Forest of Bowland (Fig. 4) imply groundwater has had limited chemical interaction time with rocks, although ion exchange processes may be responsible for the high Na-Cl ratios found in many of the Carboniferous groundwater samples.[60] Stable isotopes of δ^2H and δ^{18}O from the Millstone Grit in Lancashire indicate that groundwater is younger than 10,000 years old.[60] Likewise, isotope data from fresh groundwater in the coastal plain of the Sellafield region, ~70 km northwest of the Fylde, indicate that groundwater is younger than ~11,700 years old.[61] Groundwater flow through the Sherwood Sandstone aquifer is hypothesised to be directed towards the Wyre and Ribble estuaries (Fig. 9),[54] with horst and graben fault structures reducing east-west horizontal conductivity of the aquifer near Preston.[53]

The Woodsfold fault in the northern to central Fylde is not considered to form a groundwater flow barrier because of the continuity of the Sherwood Sandstone across it (Fig. 9). Further south, near Kirkham and Rose Acre Wood, the Woodsfold fault is considered to form a barrier to east-

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west groundwater flow based on the presence of Na-Cl type brine west of the fault (Fig. 9). The mean concentrations of sodium (51,500 ±4,000 (1σ) mg/l) and chloride (77,000 ±19,800 (1σ) mg/l) in the Kirkham Borehole SD43/20 are substantially higher than sea water (sodium ~15,400 mg/l and chloride ~19,300 mg/l), requiring concentration by the dissolution of halite or evaporation of sea water.[62] Although parts of the Mercia Mudstone Group may have formed on near-coastal plains and sabkhas,[63] the continental depositional setting of the Sherwood Sandstone Group and Mercia Mudstone Group suggests that the sodium and chloride concentrations are more likely the result of post-burial halite dissolution. However, whereas the Mercia Mudstone Group has been solution mined for halite in the northwest of the Fylde,[64] the lack of halite in the Kirkham Borehole SD43/20 at the sample depths of 240-260 m[59] suggests the brine was not formed by in situ dissolution. Alternatively, we hypothesise that halite dissolution of the Mercia Mudstone Group in the offshore East Irish Sea Basin has created brine which has migrated updip to the coastline. This process has been proposed to account for 2 Ma brine in the Sellafield region further north and is supported by the meteoric isotope composition and the 200,000 mg/l sodium chloride equivalent salinity found in the South Morecambe gas field.[61, 65] Closer to the Fylde the Hamilton and Lennox fields, with Sherwood Sandstone Group reservoirs, contain formation waters with sodium chloride equivalent salinities of 300,000 mg/l and 280,000 mg/l, respectively.[66, 67] Because brines are persistent in basins,[68] a driving force is required to explain brine migration to the Fylde. The most likely driving force is compaction from basin loading.[69, 70] Interpretation of the onshore 2D seismic reflection data indicates that the Sherwood Sandstone continues updip north-eastwards until it lies directly below the Superficial Deposits and becomes part of the principal aquifer. Assuming the sample location west of Garstang is fresh groundwater in the Sherwood Sandstone (Fig. 4), this implies a lateral TDS gradient of ~5-17 mg/l/m within the Sherwood Sandstone from 41,341 ±1 to 153,280 ±1 mg/l at Rose Acre Wood to 377 ±1 mg/l near Garstang (Fig. 9).

The saline sample at Clifton Marsh Landfill on the River Ribble estuary, EM-C at Jameson Road Landfill in the northwest Fylde, and a number of samples from Blackpool were also Na-Cl type groundwater, but with sodium and chloride concentrations less than sea water. The Clifton Marsh Landfill site has no Mercia Mudstone Group present and lies east of the compartmentalising Woodsfold fault (Fig. 9), suggesting that the sodium and chloride concentrations are not the result of in situ halite dissolution or brine mixing. Alternatively we hypothesise enrichment occurs either due to landfill leachate[71, 72] or from present day sea water intrusion mixing with the terrestrial groundwater system. The driving force for this possible sea water intrusion could be groundwater abstractions from the Sherwood Sandstone by British Nuclear Fuels Limited, which occur ~3 km north of Clifton Marsh Landfill (Fig. 9). In the northwest of the Fylde no abstractions are known to occur west of the River Wyre at EM-C, although groundwater pumping has occurred ~3 km to the east at the Preesall Salt Field.[64] The sodium and chloride concentrations found in EM-C could be the result of landfill leachate, saline intrusion (from sea water or Na-Cl type groundwater) driven by the nearby pumping, or in situ halite dissolution (Fig. 9). Groundwater connection between west of the River Wyre and Blackpool, where the calcium dominated EM-B is located, may be restricted by the Preesall fault and/or stratigraphic changes (Fig. 9). Samples from Blackpool show a range of TDS values, EM proportions and relative major ion concentrations, indicating stratigraphic compartmentalisation in the Superficial Deposits. Five samples had TDS values ≥4288 ±1 mg/l and were enriched in sodium and chloride. The source of sodium and chloride is unknown, but could be related to anthropogenic inputs from Blackpool, halite dissolution in the underlying Mercia Mudstone Group, or sea water intrusion, although we know of no groundwater abstractions to drive this process.

6.3. *Study limitations*

Identifying groundwater compartmentalisation across an area with no monitoring programme dedicated to its detection is dependent on the availability and quality of historical data. From the map figures in this study it can be seen that groundwater across large areas of the Bowland Basin is not sampled. Prediction of groundwater properties away from sampled locations required extensive

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interpolation in some areas, which increases uncertainty in the predicted groundwater properties. Importantly this also means the influences of known faults or stratigraphic changes on groundwater are unknown in these areas.

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Secondly, the EA Water Quality Archive does not contain any information on the depth or aquifer that groundwater samples were taken from. To provide some depth control we matched the EA sampling locations with boreholes from the BGS Onshore GeoIndex where possible. Despite matching 71 of the 96 locations, 41 of the sample locations had unknown sampling depths. Consequently, a large proportion of the groundwater samples could not be tied to specific geological formations, which in turn made it difficult to distinguish the cause of changes in groundwater quality. For example, a lateral change from fresh to brackish groundwater could be the result of structural compartmentalisation by a fault, stratigraphic compartmentalisation by a change in geological formation, or simply that the brackish sample was taken at greater depth in the same formation (assuming salinity increases with depth). Furthermore, the current groundwater monitoring is relatively shallow (the deepest borehole being 445 m) compared to current shale exploration depths (~2000 m), so little is known about deep groundwater in the Bowland Basin. It may be possible to use wireline logs, pressure tests, and geochemical data from petroleum boreholes to interpret the deeper groundwater system, for example using resistivity logs to estimate salinity. However, these data were not available for this study.

Previous studies on groundwater compartmentalisation have made use of groundwater level data.[17] In the Bowland Basin regular measuring of groundwater levels takes place for the Sherwood Sandstone in the eastern Fylde[30] and these data have been used extensively for aquifer modelling.[50, 54] Regular groundwater level monitoring is rare or non-existent in the western Fylde, but some historic water levels can be obtained through the BGS Borehole record viewer. The compilation and analysis of these data is beyond the timeframe for this study. However, future work should look to compliment the current study with these historic groundwater level data.

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The extent and quality of the seismic reflection data also limit the analysis of compartmentalisation. The 2D seismic reflection lines in the Bowland Basin generally trend north-south and east-west but the grid coverage is highly non-uniform due to surface restrictions and survey purposes. The lines also vary in acquisition age (1979-1999), acoustic source types (explosive charges and Vibroseis), and processing workflows. Consequently, the quality, resolution and depths of the lines vary, complicating the interpretation of horizons and faults across lines. Furthermore, petroleum boreholes across the Bowland Basin are relatively sparse, limiting the number of well ties that can be made to constrain the geological interpretation.

6.4. Implications for fracking

Groundwater compartmentalisation is important for determining the potential migration routes and receptors of fracking fluid contaminants because it can create groundwater flow directions different to regional trends.[22, 23] Where basins and groundwater flow extend across multiple jurisdictions this could be important because each jurisdiction may have different groundwater management legislation.[23] Compartmentalisation is also important because it can discourage lateral groundwater flow and encourage upward flow in the presence of a vertical head gradient.[14] A compartmentalised basin may therefore create compartments with higher vulnerabilities to contamination because regional lateral groundwater flow cannot dilute any fracking fluid contaminants. This effect is hypothesised to be greatest when faults strike perpendicular to the regional flow direction, thereby creating areas of reduced or no flow.[23] Conversely, isolated compartments could prevent the regional movement of contaminants; contaminants would be restricted to the compartment they originate from, thereby protecting surrounding aquifers in neighbouring compartments.[17]

For the Bowland Basin we identified a number of possible examples of compartmentalisation, suggesting that areas of the Bowland Basin are compartmentalised. Consequently, some areas within the basin may be more, or less, vulnerable to contamination from the potential upward migration of fracking or formation fluids. Identification of compartmentalisation is not currently required under regulations for fracking in England but, because it is an important hydrogeological effect, it should be considered in environmental risk assessments for the long-term migration of fracking fluid contaminants. The current data available for analysis are too spatially limited to adequately assess compartmentalisation across the Bowland Basin and in particular, the influence of known faults on groundwater flow. This study therefore highlights that to adequately identify groundwater compartmentalisation in a prospective shale basin, historical groundwater data may need to be supplemented with a dedicated basin-wide groundwater sampling programme. Furthermore, historical seismic reflection data may need to be complemented by dedicated seismic lines or three-dimensional surveys to cover areas of poor coverage or quality.

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7. Conclusions

Groundwater compartmentalisation is an important consideration in the long-term migration of fracking fluid contaminants and can be both an advantage and disadvantage; compartmentalisation can create compartments of high vulnerability but may also prevent the regional spread of contaminants. Compartmentalisation can be caused by structural or stratigraphic changes and historic groundwater quality data can be integrated with subsurface geological data to identify it. In the prospective Bowland Basin examples of compartmentalisation were identified using 2D seismic reflection data combined with groundwater quality data. However, many areas and faults in the Bowland Basin remain untested by historical groundwater sampling. Seismic reflection data are also two dimensional across much of the basin and vary in quality due to processing techniques and acquisition ages and methods. Therefore, the adequate identification of compartmentalisation in prospective shale basins may require supplementing historical data with dedicated basin-wide groundwater sampling programmes and the acquisition of new seismic data in areas of poor coverage or quality.

Conflicts of interest

There are no conflicts to declare.

Acknowledgments

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Figure captions

Figure 1

Map showing the study area in northwest England (black outlined rectangle and infilled red rectangle on inset map) with the locations of sampled groundwater boreholes, the fracking sites of Preston New Road (PNR) and Rose Acre Wood (RAW), the Kirkham Borehole SD43/20 (KH), the 2D seismic lines from figure 8, BGS mapped linear features, and the prospective area of the Bowland Shale.[24] Contains Ordnance Survey and British Geological Survey data © Crown copyright and database right (2018). An British Geological Survey/EDINA supplied service.

Figure 2

Map showing the extent of interpreted seismic horizons. Also shown are BGS mapped linear features and the fracking sites of Preston New Road (PNR) and Rose Acre Wood (RAW). The Top Sherwood Sandstone is eroded in the north and east and is confined by the Mercia Mudstone Group towards the southwest. Contains British Geological Survey data © Crown copyright and database right (2018). An British Geological Survey/EDINA supplied service.

DOI: 10.1039/C8EM00300A

Figure 3

Interpolated groundwater maps of (a) alkalinity to pH 4.5 as $CaCO_3$, (b) calcium, (c) conductivity at 25°C, (d) magnesium, and (e) potassium in the Bowland Basin. Also shown are BGS mapped linear features. KH is the Kirkham Borehole SD43/20. Contains British Geological Survey data © Crown copyright and database right (2018). An British Geological Survey/EDINA supplied service.

Figure 4

Map showing the 90 locations where groundwater TDS was estimated. Also shown are BGS mapped linear features and the fracking sites of Preston New Road (PNR) and Rose Acre Wood (RAW). KH is the Kirkham Borehole SD43/20 and CML is Clifton Marsh Landfill. Contains Ordnance Survey and British Geological Survey data © Crown copyright and database right (2018). An British Geological Survey/EDINA supplied service.

Figure 5

(a) Piper plot, (b) Gibbs plot, (c) Chloride versus sodium concentration plot, and (d) Na:Cl ratio versus chloride concentration plot of 90 locations where major cations and anions were measured. A sea water chloride concentration of 19,300 mg/l and an Na:Cl ratio of 0.5567 are used for reference.[73, 74]

Figure 6

Principal components plots of (a) PC2 versus PC1, (b) PC3 versus PC2, and (c) PC3 versus PC1 of 56 locations. Interpreted end-members (EM), trends (arrows) and outliers (shaded areas) are labelled. The minimum TDS concentration for the outlier samples with high TDS is 4288 ±1 mg/l.

Figure 7

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Map showing the locations of the three end-member (EM) groundwater types and their dominance (taken as ≥50%) at 40 other locations. Also shown are BGS mapped linear features. CML is Clifton Marsh Landfill. Contains Ordnance Survey and British Geological Survey data © Crown copyright and database right (2018). An British Geological Survey/EDINA supplied service.

Figure 8

Interpreted 2D seismic reflection lines which provide evidence for compartmentalisation, (a) the east-west line GC82-342_RM and, (b) the north-south line GC87-382_OM. Line locations are shown by labelled white lines in figure 1.

Figure 9

Conceptual hydrogeological model for the Bowland Basin, including the locations of Preston New Road (PNR), Rose Acre Wood (RAW), Jameson Road Landfill (JRL), Clifton Marsh Landfill (CML), and groundwater abstractions by British Nuclear Fuels Limited (BNFL). The use of confined and unconfined is with respect to the presence and absence of the Mercia Mudstone Group, respectively.

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Figure 1

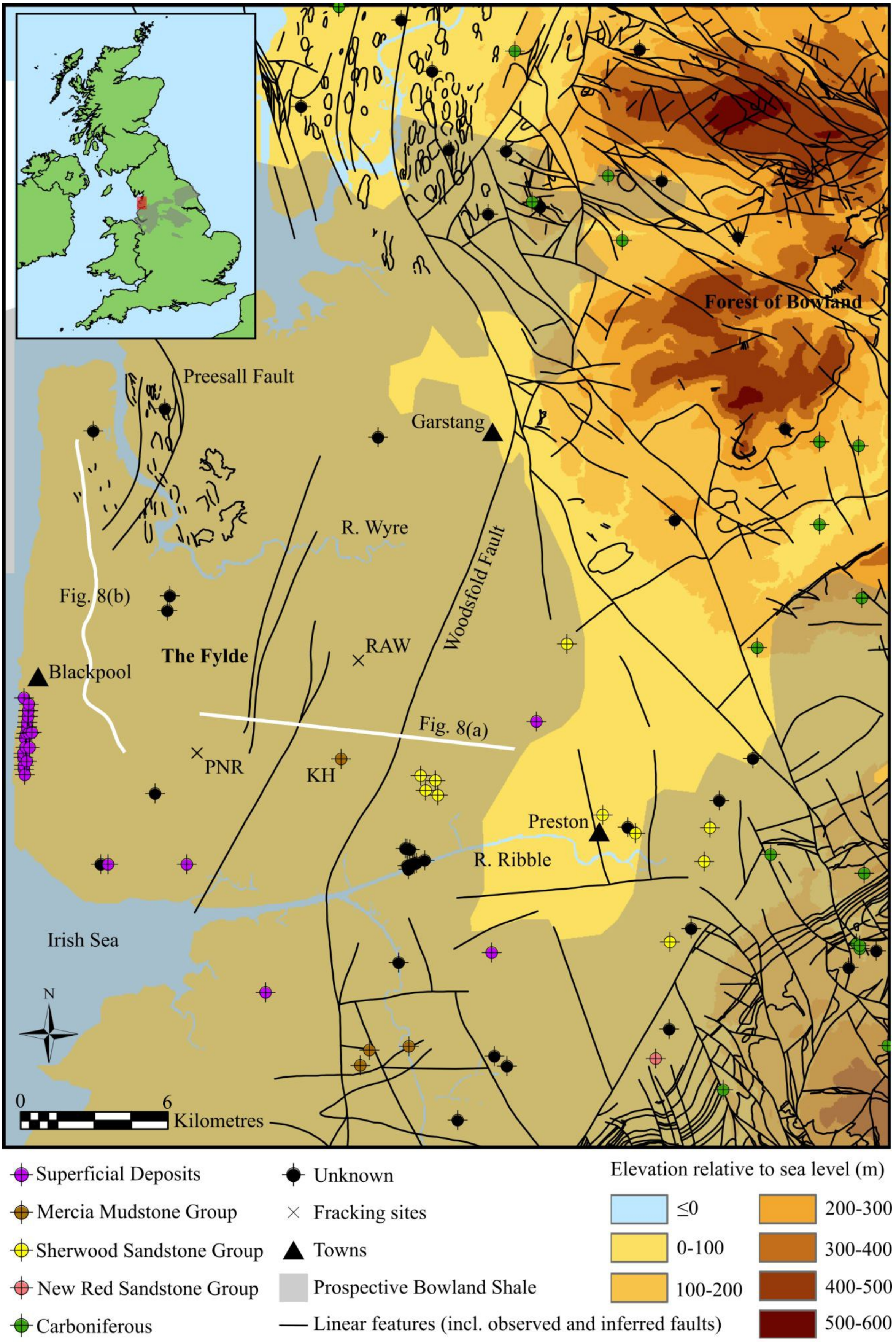

Figure 2

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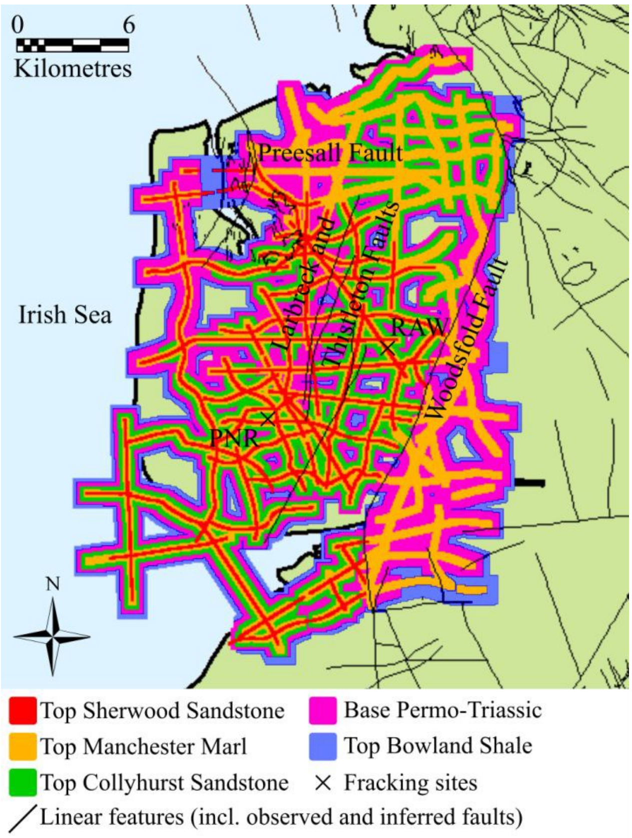

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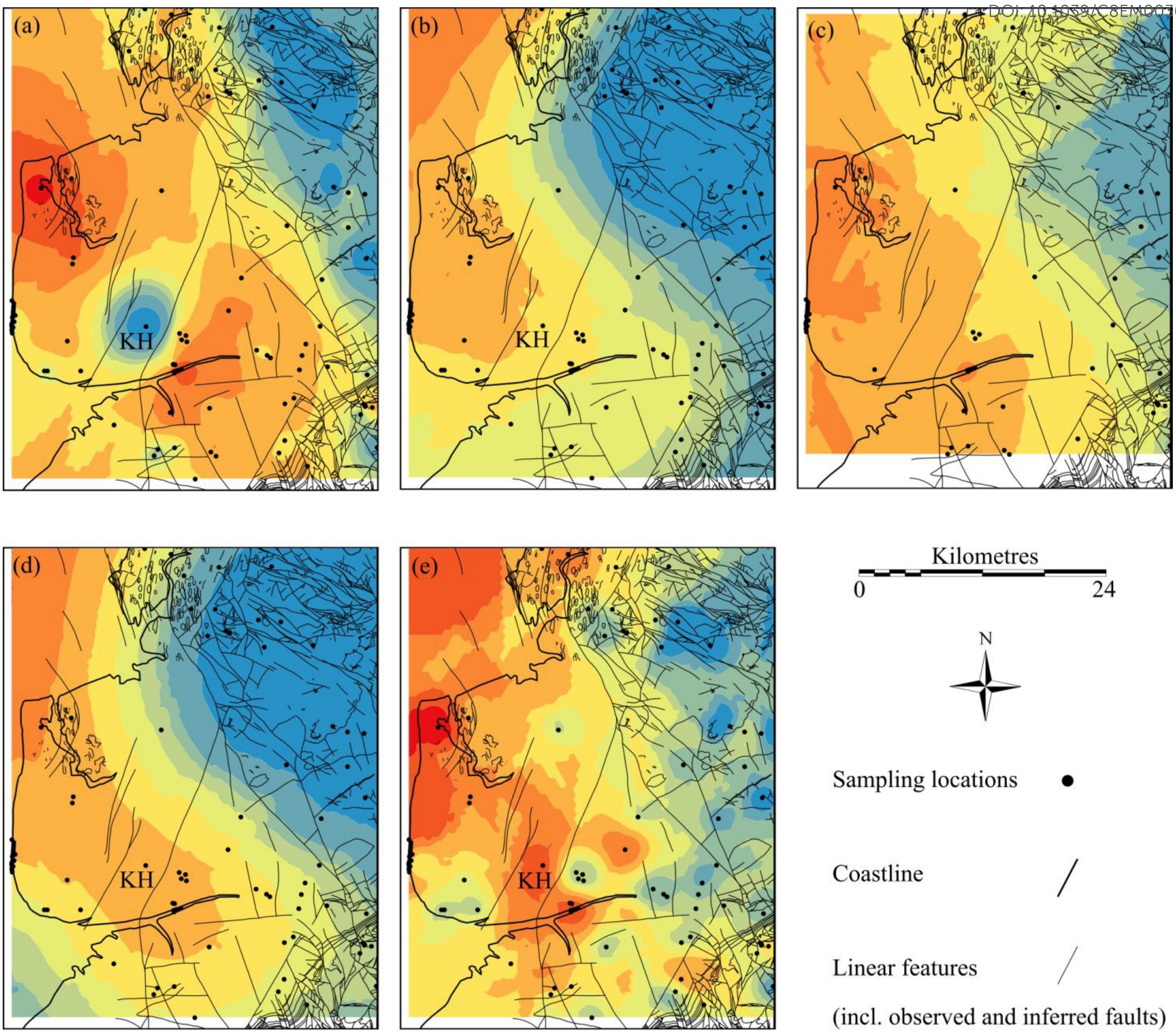
Figure 3



	Alkalinity to pH 4.5 as $CaCO_3$ (mg/l)	Calcium (mg/l)	Conductivity at 25°C (μS/cm)	Magnesium (mg/l)	Potassium (mg/l)
	5.0-109.1	1.2-41.4	107.0-438.6	0.3-9.8	0.6-1.6
	109.1-176.1	41.4-65.8	438.6-603.4	9.8-14.8	1.6-2.2
	176.1-219.3	65.8-80.5	603.4-685.2	14.8-17.4	2.2-3.1
	219.3-247.2	80.5-104.9	685.2-850.0	17.4-22.4	3.1-4.8
	247.2-290.3	104.9-145.1	850.0-1181.6	22.4-31.9	4.8-7.8
	290.3-357.4	145.1-211.3	1181.6-1849.1	31.9-49.8	7.8-12.8
	357.4-461-5	211.3-320.4	1849.1-3192.8	49.8-83.8	12.8-21.4
	461.5-623.0	320.4-500.2	3192.8-5897.4	83.8-148.4	21.4-36.1
	623.0-873.8	500.2-796.5	5897.4-11341.6	148.4-270.7	36.1-61.3
	873.8-1263.1	796.5-1285.0	11341.6-22300.0	270.7-502.5	61.3-104.7

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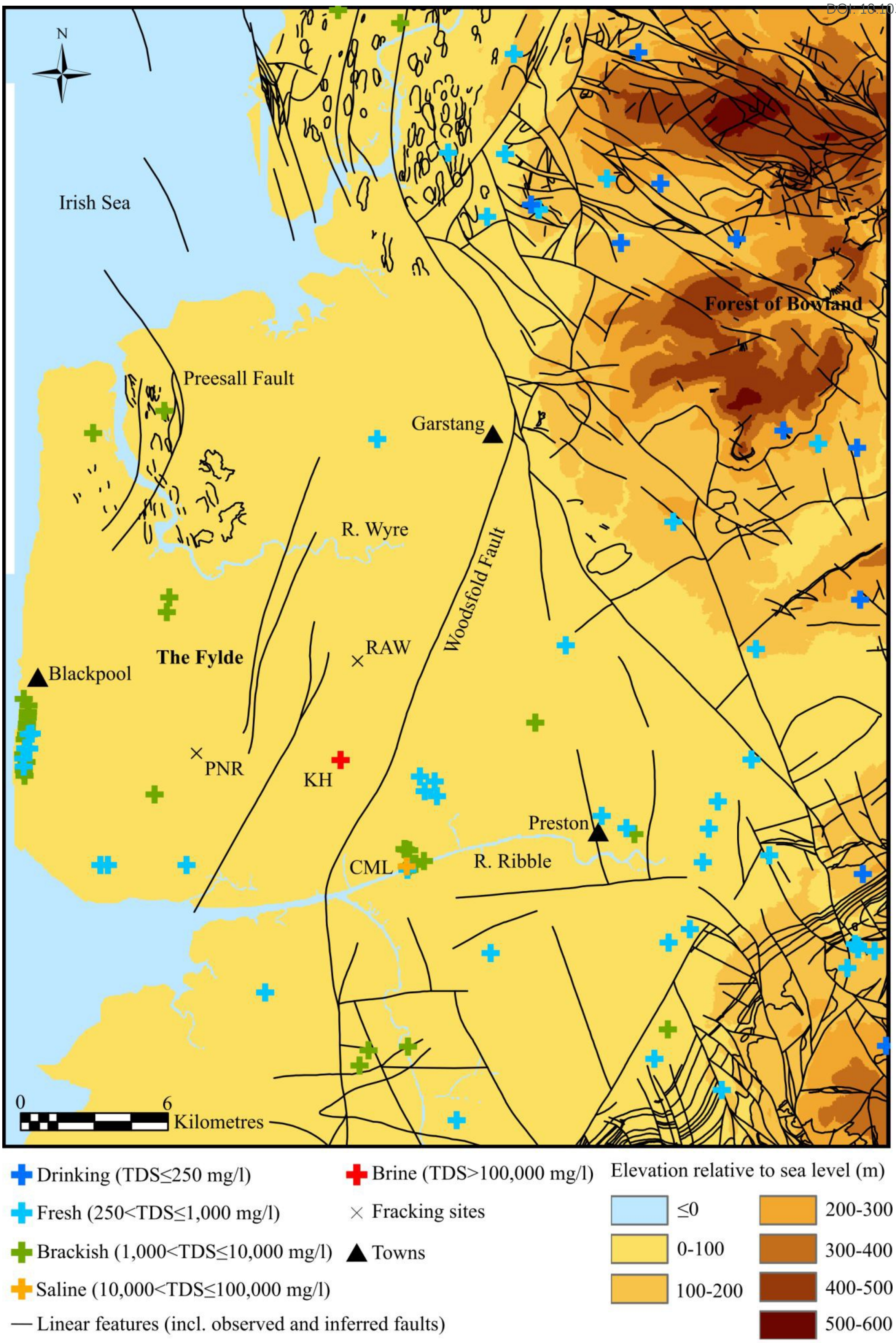
DOI: 10.1039/C8EM00300A

Figure 4



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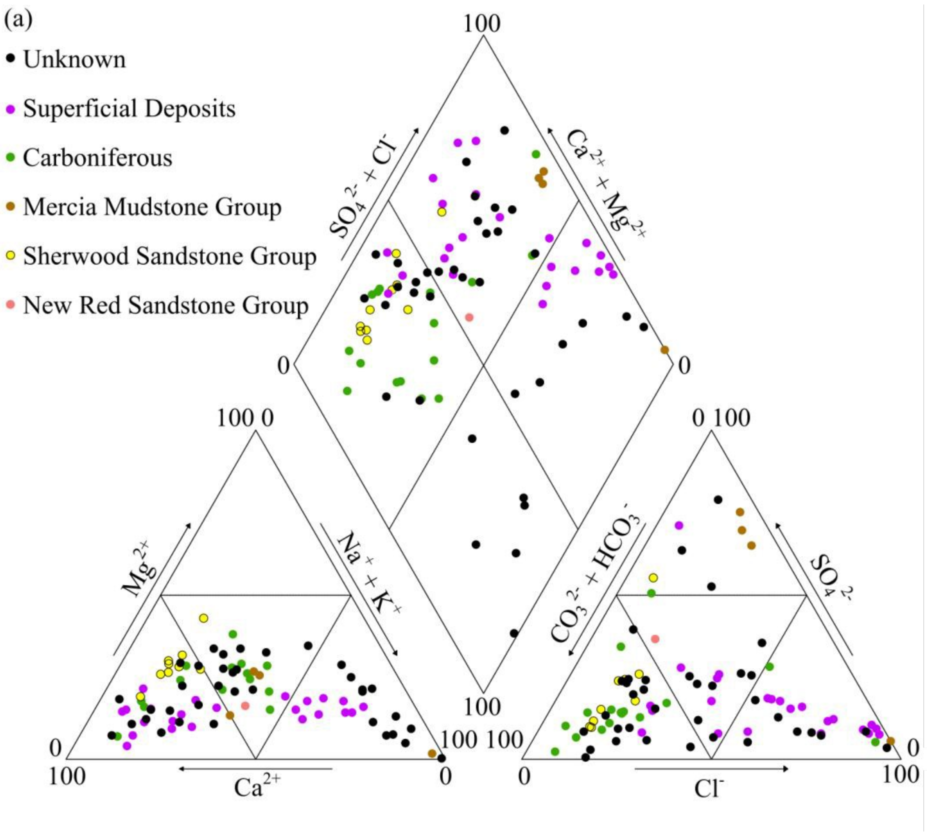
DOI: 10.1039/C8EM00300A

Figure 5(a)



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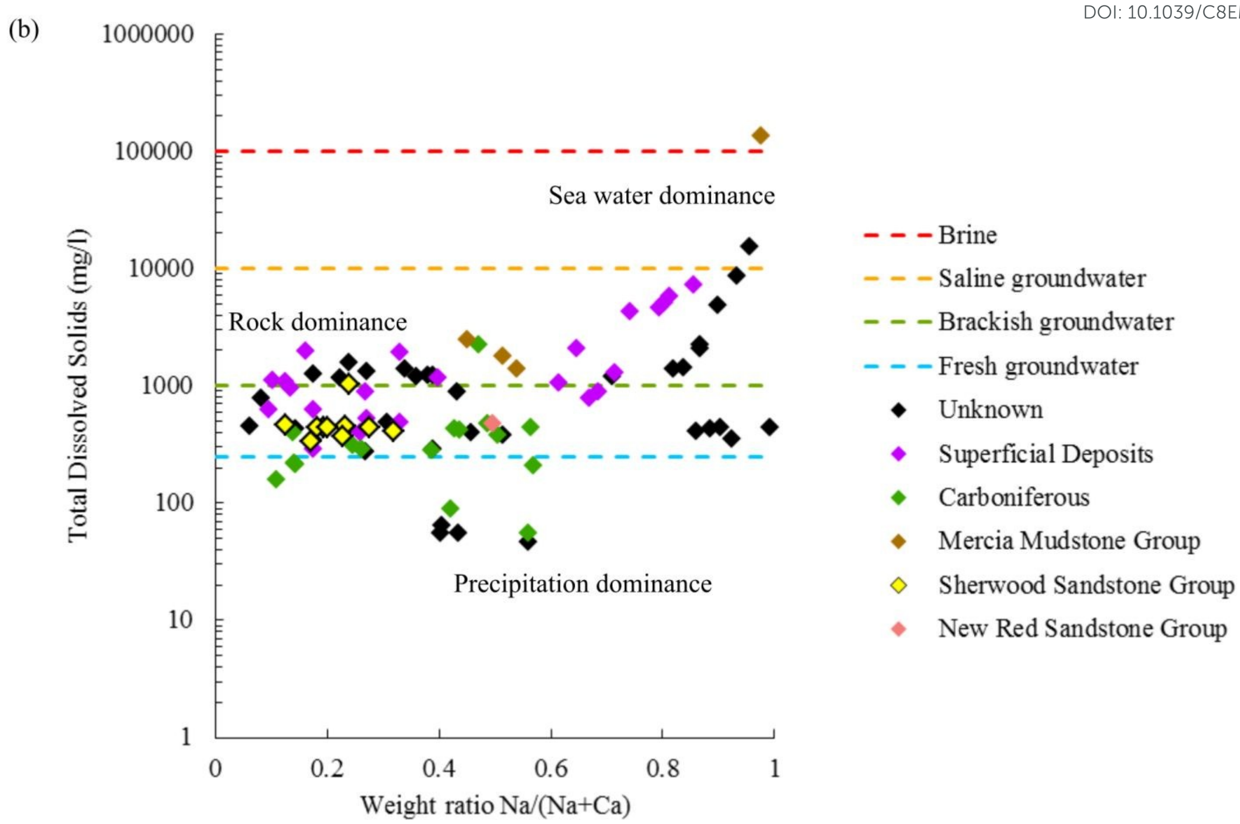

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View Article Online
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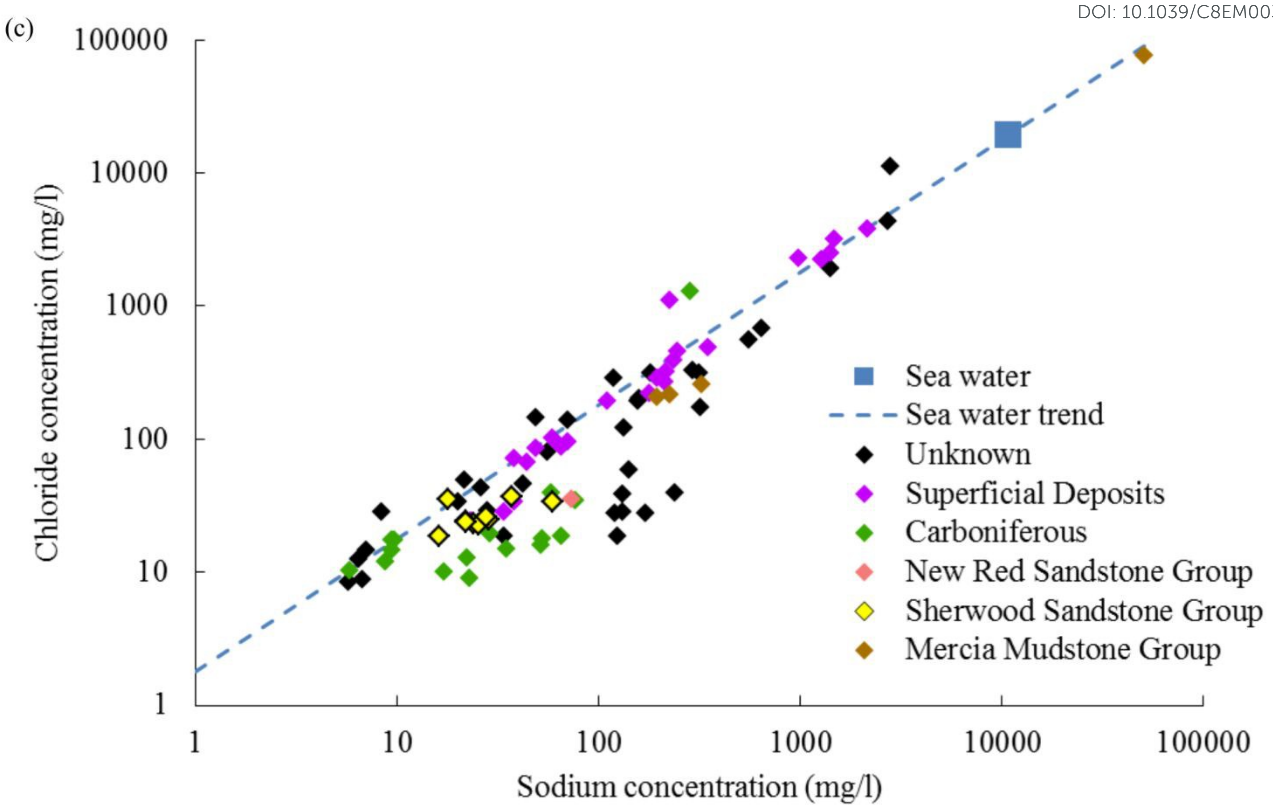

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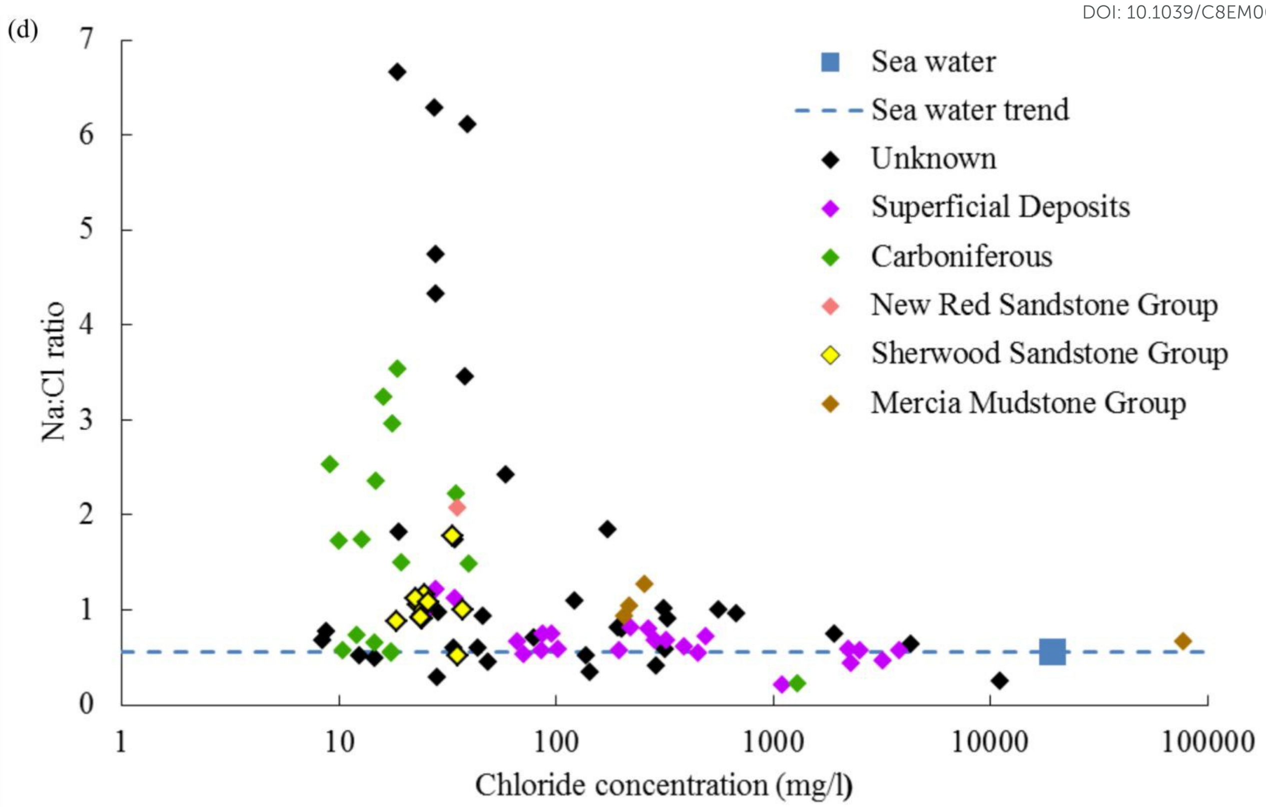

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View Article Online
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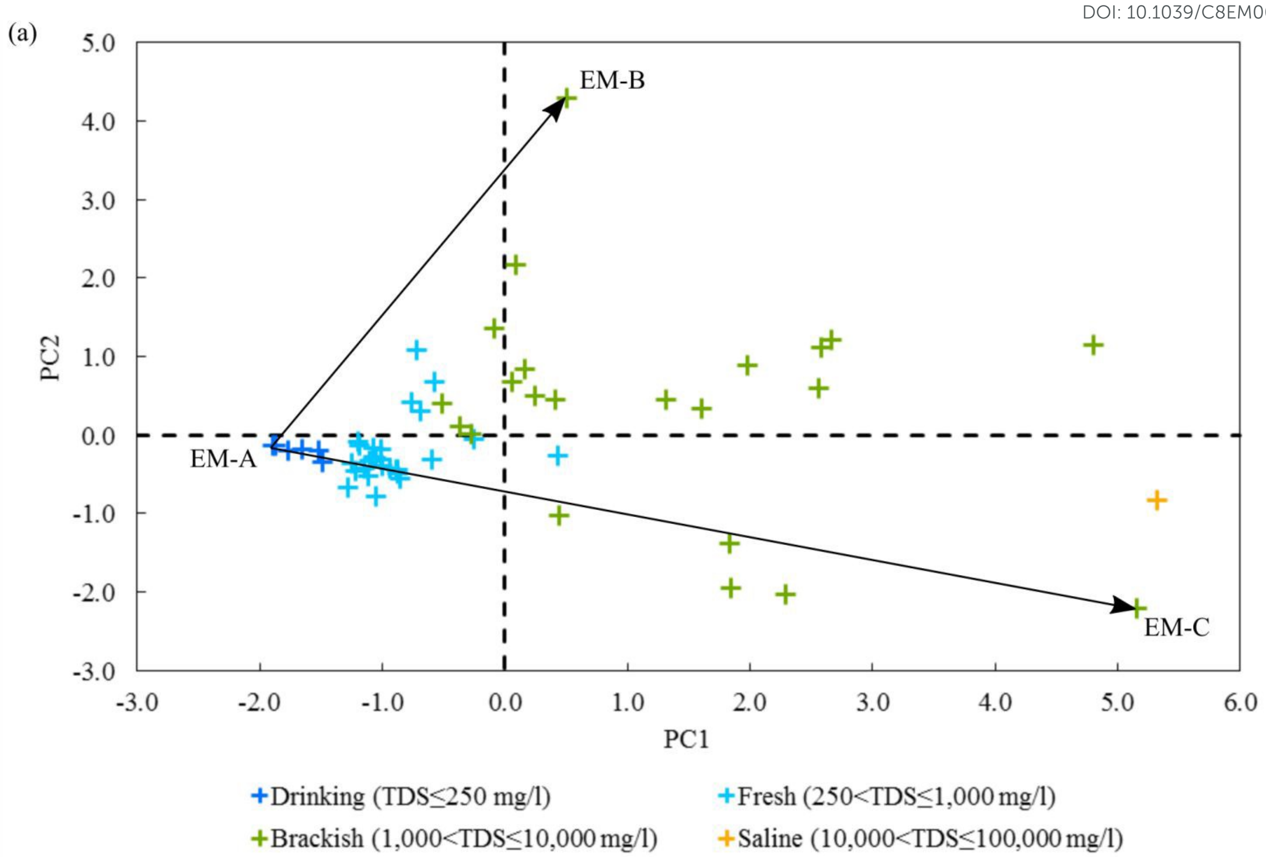

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View Article Online
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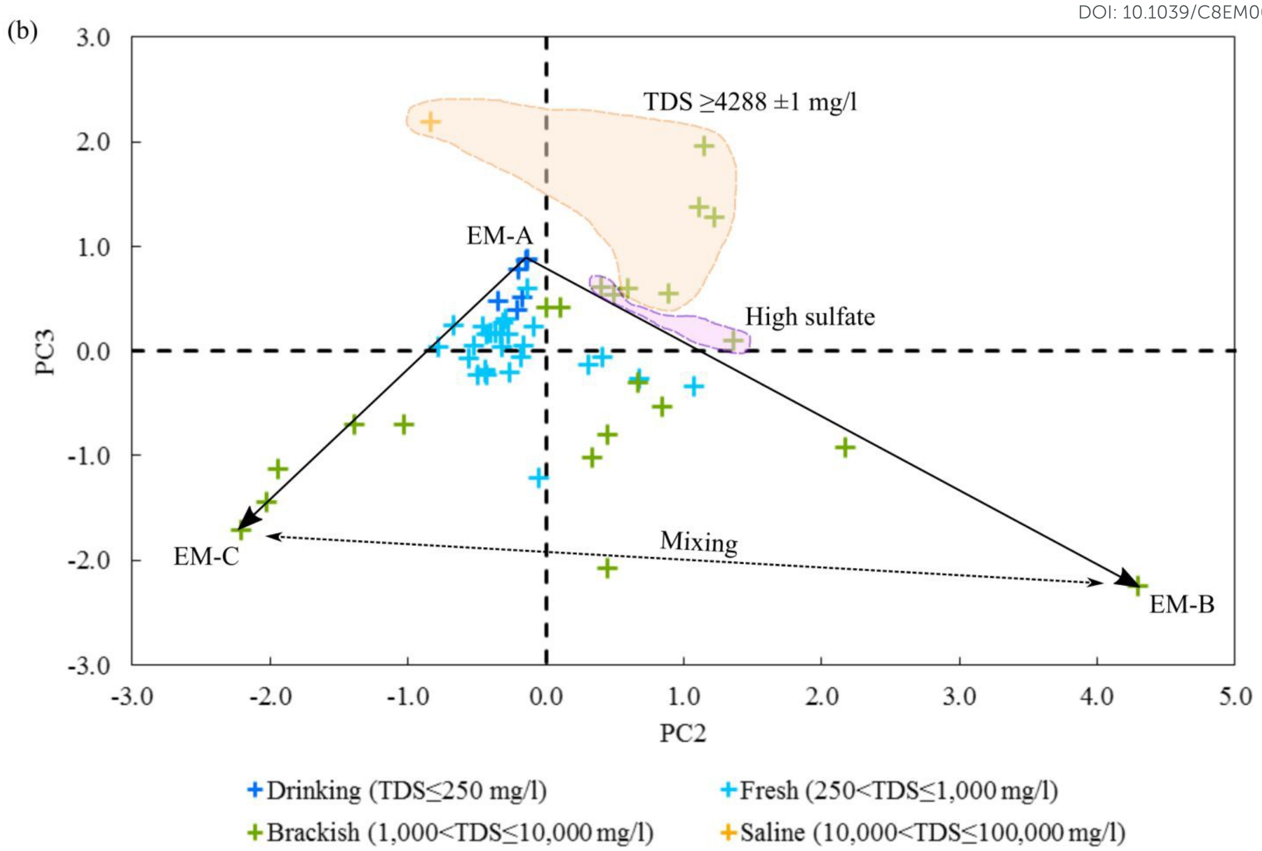

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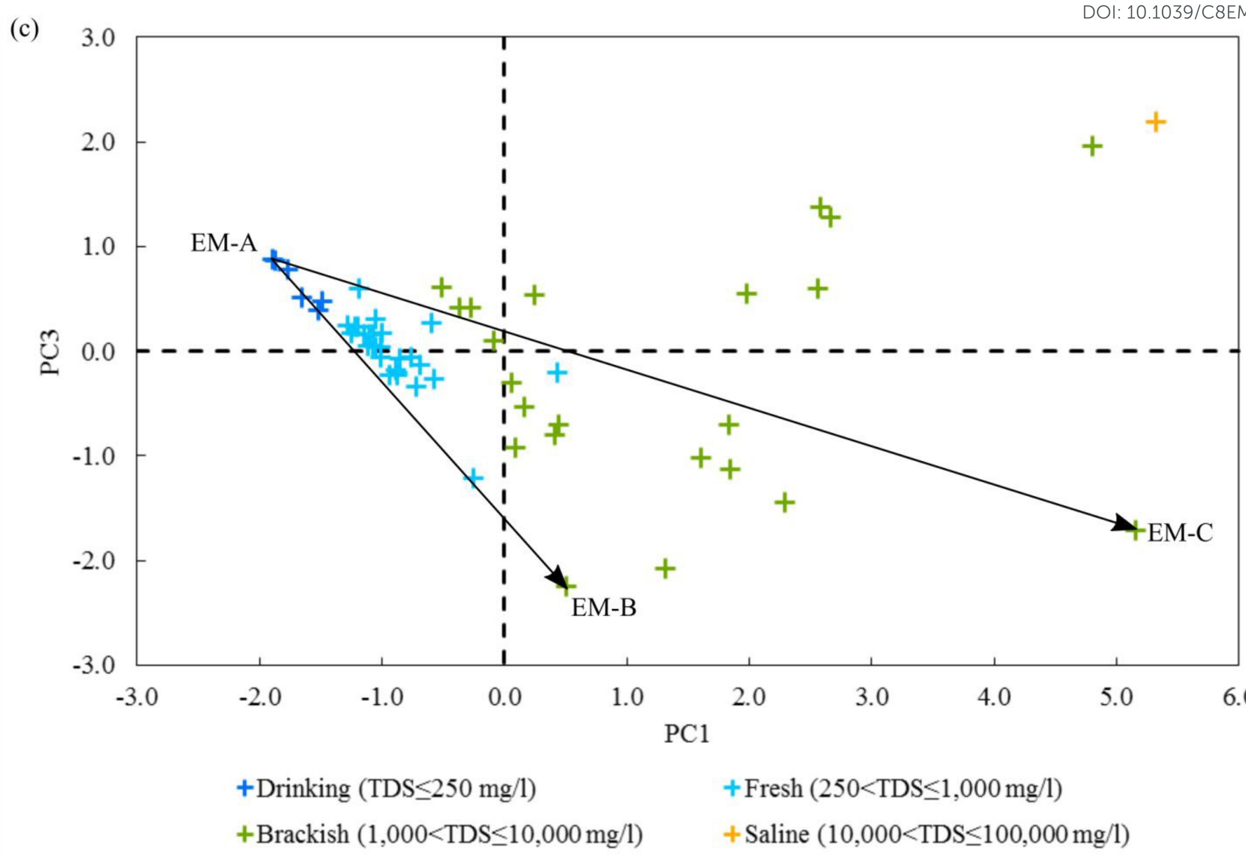

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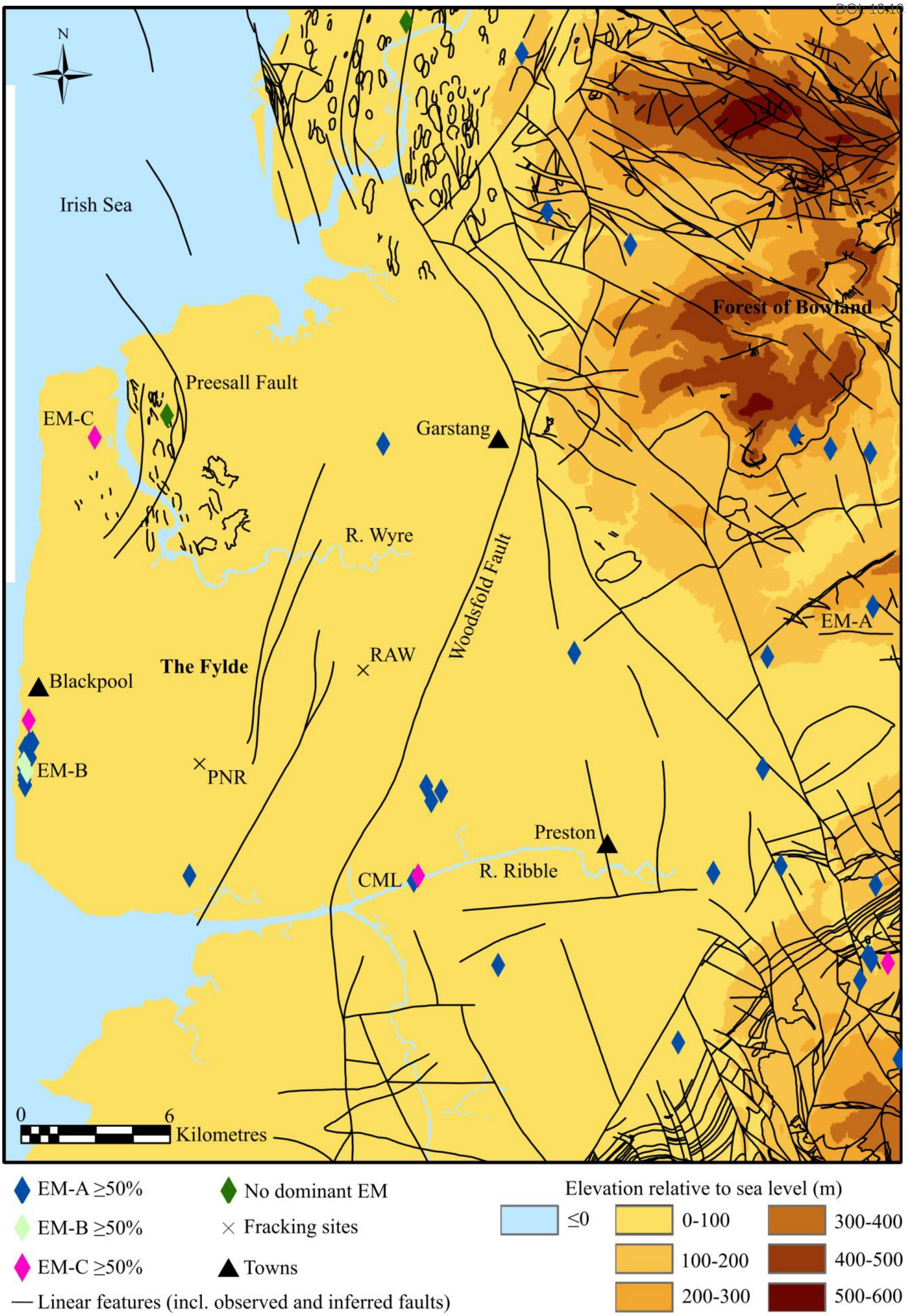
DOI: 10.1039/C8EM00300A

Figure 7



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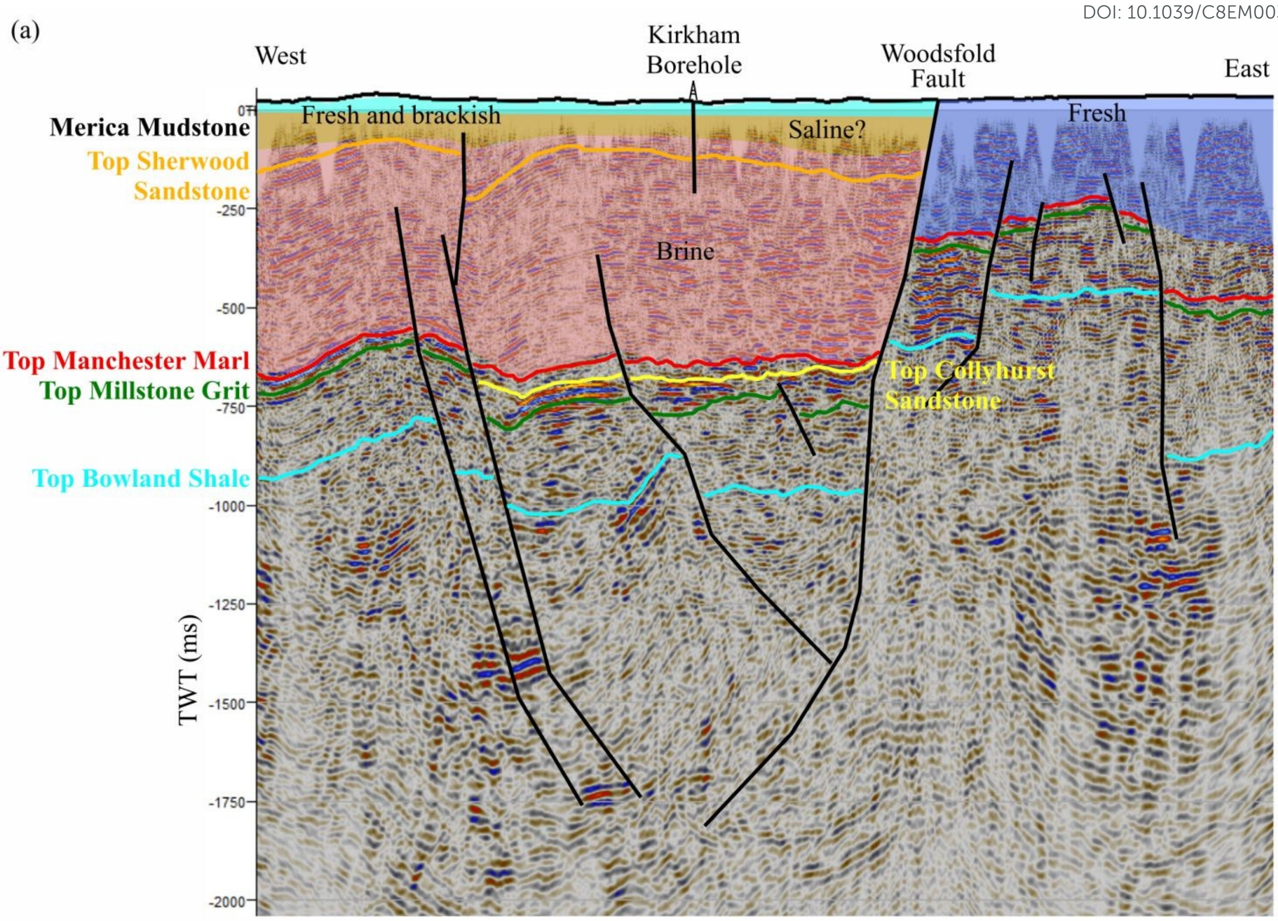
DOI: 10.1039/C8EM00300A

Figure 8(a)



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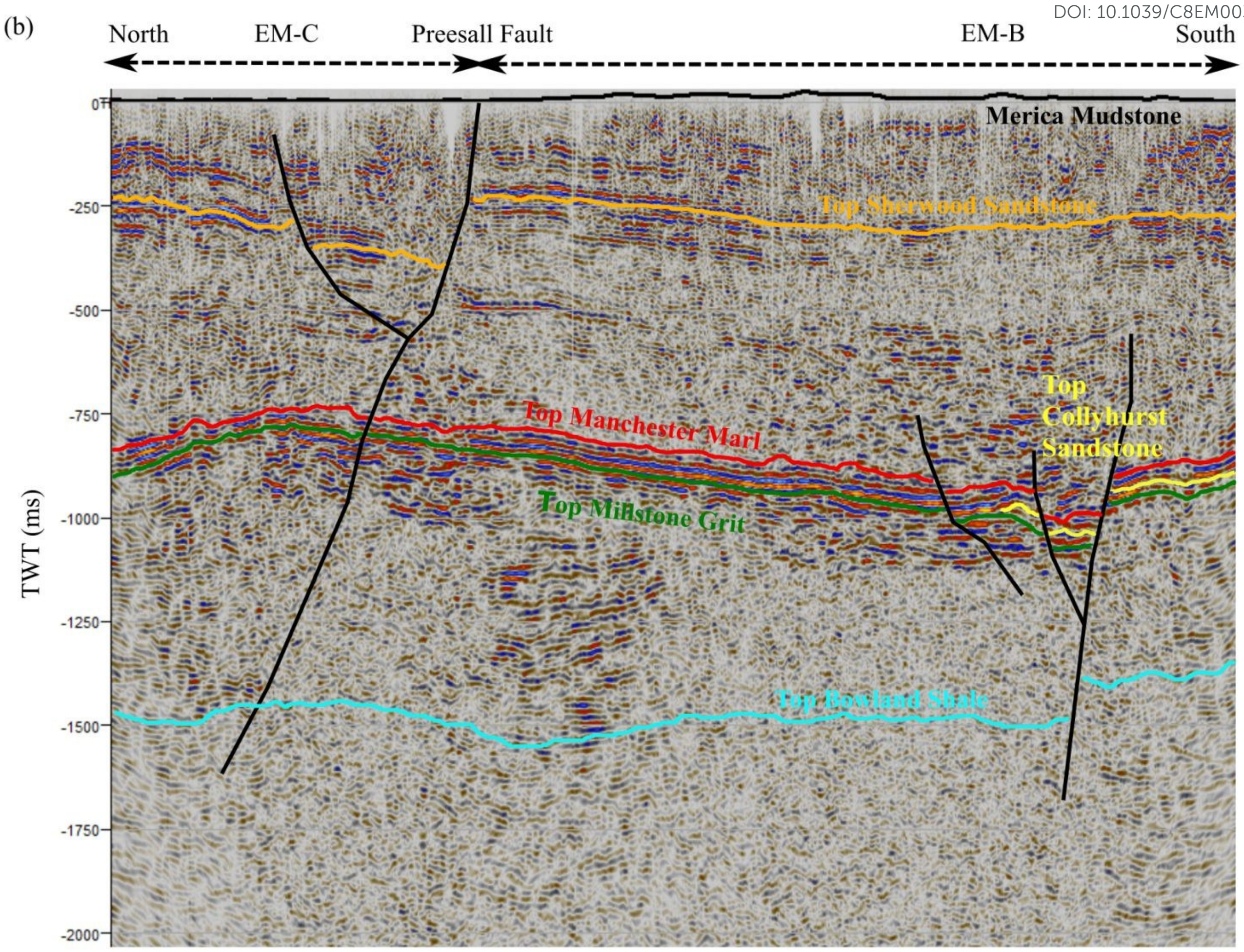

Figure 9

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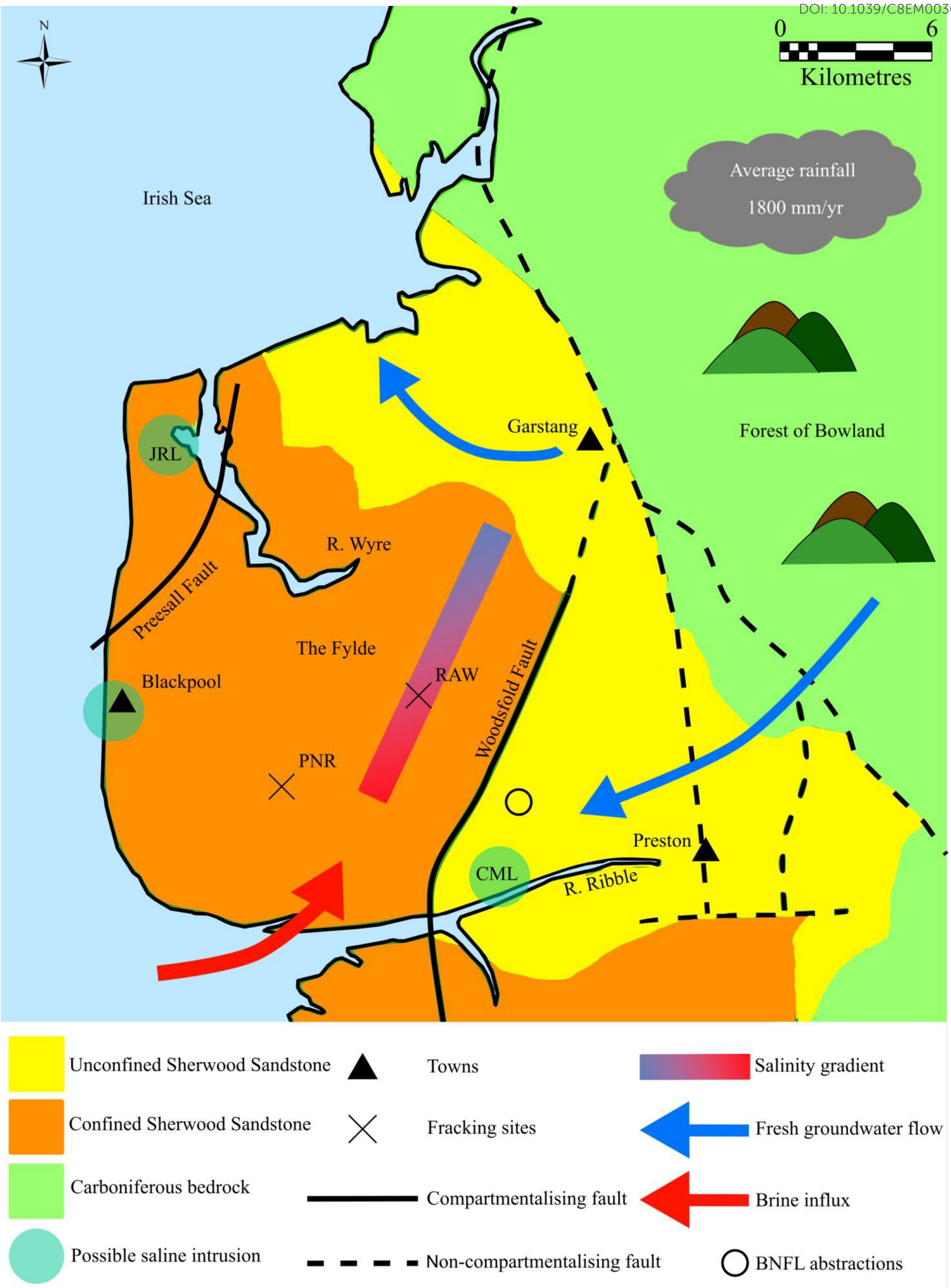

Identifying groundwater compartmentalisation for hydraulic fracturing risk assessments

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Table of contents entry

Groundwater quality and seismic reflection data are combined to identify compartmentalisation in the Bowland Basin, northwest England. Thereby providing a method that could be applied to other prospective shale basins.